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ANALYTICAL STUDY OF EFFECTS OF SURFACE AND ENVIRONMENTAL THERMAL PROPERTIES ON MOISTURE IN COMPOSITES

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16. Abstract

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ANALYTICAL STUDY OF EFFECTS OF SURFACE AND ENVIRONMENTAL THERMAL PROPERTIES ON MOISTURE IN COMPOSITES

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SUMMARY

An analytical, parametric study has been made of the influence of surface and environmental thermal properties on the moisture absorption in fiber-reinforced polymeric-resin-matrix composite materials which have been subjected to convection and solar radiation. Predicted moisture contents based on the conditions at the heated surface and in the ambient air were compared for both short-time and long-time exposures over a wide range of values for emittance, solar absorptance, convective heat-transfer coefficient, solar radiation, ambient temperature, and orientation of the surface with respect to the Sun. The calculations showed that absorptance and heat-transfer coefficient have significant effects on the moisture content.

INTRODUCTION

Fiber-reinforced polymeric-resin-matrix composite materials provide lightweight structures for aerospace application because of the high-strength, stiffness, and low-density properties of these materials. These materials are being used for secondary aerospace structures and are being considered for primary structures. Studies have shown that these materials pick up moisture from the atmosphere and that this moisture absorption results in significant degradation of matrix-sensitive mechanical properties at moderately elevated temperatures. (See refs. 1 and 2.) An understanding of the parameters affecting moisture absorption by these materials is required before reliable long-term aircraft structures can be designed.

The diffusion of moisture in polymeric-resin composites and the effect of moisture on mechanical properties have been studied both experimentally and analytically (refs. 3 to 5). Reference 3 shows that the equilibrium moisture content in the composite is primarily a function of the relative humidity of the environment. Analytical studies (e.g., refs. 3 and 4) generally assume that the relative humidity and temperature of the air at the surface are the same as those of the ambient air. However, if the surface is exposed to convection and solar radiation, the temperature and relative humidity at the surface may be very different from those of the ambient environment. Reference 5 predicts that the moisture content of a composite panel heated by the Sun is about 30 percent less than the moisture content of a shaded panel.

The objective of this study was to determine analytically the sensitivity of moisture content to surface and environmental parameters. The parameters varied were: (1) solar absorptance, (2) surface emittance, (3) convective

heat-transfer coefficient, (4) solar radiation, (5) ambient temperature, and (6) surface orientation relative to the Sun. Moisture content was calculated over a wide range of values for these parameters and compared with calculations based on ambient conditions. Results for both short-time and long-time exposures were determined.

SYMBOLS

a,b	constants in equation (4)
D	diffusion coefficient normal to surface
D_o	permeability index
E	activation energy
G	parameter defined by equation (5)
h	convective heat-transfer coefficient
M	moisture content
M_{eq}	equilibrium moisture content
p_s	pressure of saturated vapor
p_v	vapor pressure
q	solar radiation incident on panel surface normal to Sun
q_d	diffuse sky radiation
R	universal gas constant
s	thickness
T	temperature
T_e	effective sky temperature
t	time
α	solar absorptance
ε	surface emittance
σ	Stefan-Boltzmann constant

ϕ relative humidity

ψ angle between normal to panel surface and Sun, that is, surface orientation

Subscripts:

a ambient condition

i initial condition

ANALYSIS

A large, thin panel of resin-matrix composite, insulated on one side (perfect thermal insulation, impermeable to moisture) and exposed on the other side to a moist-air environment with convection and solar radiation, was considered. The environment was assumed to be constant with respect to time. A calculation showed that, under these conditions, a typical graphite-epoxy panel 18 mm thick (12 plies) reached a uniform temperature in less than one-half hour. Therefore, the panel was assumed to be at a uniform temperature. The panel moisture content depended on the panel temperature and the relative humidity of a boundary layer of air at the panel surface. The panel temperature T was determined from the surface energy balance

$$h(T - T_a) + \sigma\varepsilon\left(T^4 - T_e^{4}\right) = \alpha q \cos\psi + q_d \tag{1}$$

where, from reference 6, the effective sky temperature T_e equals $0.0552T_a^{1.5}$. The diffuse sky radiation q_d in equation (1) was assumed to be 10 percent of the direct solar radiation incident on the panel (ref. 7). Radiation from the ground or surroundings was not included in equation (1). The temperature of the boundary layer of air at the panel surface was assumed to be the same as the temperature of the panel but different from the ambient temperature.

The relative humidity of the air was determined with the relationship

$$\phi = \frac{p_v}{p_s} \tag{2}$$

The dry air, water vapor, and mixture were assumed to behave as perfect gases. The absolute humidity was assumed to be constant. Properties for the saturated vapor were found in reference 8.

The total moisture content of a composite at any time t due to one-dimensional diffusion (ref. 4) was approximated by

$$M = G(M_s - M_i) + M_i \tag{3}$$

where

$$M_{eq} = a\phi^b \tag{4}$$

$$G = 1 - \exp\left[-7.3\left(\frac{Dt}{4s^2}\right)^{0.75}\right] \tag{5}$$

and

$$D = D_o \exp(-E/RT) \tag{6}$$

The equilibrium moisture content M_{eq} for some materials has been found to be a linear function of relative humidity (ref. 3). In the present analysis, the exponent b in equation (4) was assumed to be one.

So as to provide a measure of changes in moisture content with changes in the parameters of the energy balance (eq. (1)), a moisture-content ratio M/M_a was defined. This is the ratio of the predicted moisture content based on panel-surface conditions to the predicted moisture content based on ambient conditions. Both long-time (steady-state) and short-time exposures were considered.

For long-time or steady-state exposure, $G = 1$ and the moisture-content ratio reduces to

$$\frac{M}{M_a} = \frac{\phi}{\phi_a} \tag{7}$$

Even though diffusion of moisture into composites is a very slow process, the short-time results should be important. Short-time results determine the condition of the surface layers of the material, and the surface layers strongly affect the flexural properties of the material. (See ref. 9.) For convenience and for correlation with data, total moisture content was chosen to represent the state of the material after short-time exposure. A detailed description of the moisture gradients at the surface requires a more complex analysis than used here. A simplified expression for the moisture-content ratio for short-time exposure was obtained by rewriting equation (5) as

$$G = 1 - \exp(-x) \tag{8}$$

where $-x$ replaces the bracketed term in equation (5). For $x \leqq 0.1$,

$$\exp(-x) \approx 1 - x$$

and, therefore,

$$G = x$$

Then, by assuming $M_i = 0$, the moisture-content ratio reduces to

$$\frac{M}{M_a} = \frac{\phi}{\phi_a}\left(\frac{D}{D_a}\right)^{0.75} = \frac{\phi}{\phi_a}\left[\frac{\exp(-E/RT)}{\exp(-E/RT_a)}\right]^{0.75} \qquad (9)$$

With $E = 7525$ cal/mole (for T300/5208 graphite epoxy composite from ref. 10) and a panel thickness of 18 mm (12 plies), the requirement for $x \leqq 0.1$ corresponds to times of about 110 and 40 hr or less when the panel temperatures are 300 and 320 K, respectively. The numerator and denominator in equation (9) are for the same material, panel geometry, and exposure time. Note that equation (9) includes the temperature dependence of the diffusion coefficient which is absent from the steady-state relationship of equation (7). The value of initial moisture content M_i was set equal to zero in all cases to show more clearly the effects on the moisture ratio of changes in the parameters.

The value of the moisture ratio may be greater or less than one, depending upon the relative values of T, T_a, and ϕ_a. However, the ratio cannot exceed a value of one for the special case where $\phi_a = 100$ percent.

RESULTS AND DISCUSSION

Moisture-Ratio Variations

Variations in the moisture-content ratio M/M_a over a wide range of solar absorptance α, surface emittance ε, convective heat-transfer coefficient h, ambient temperature T_a, and surface orientation ψ are shown in figures 1 to 5. The reference value chosen for each parameter was $\alpha = 0.9$, $\varepsilon = 0.9$, $h = 11.4$ W/m^2-K, $T_a = 294$ K, and $\psi = 0$. Results for both short-time exposure (eq. (9)) and long-time (steady-state) exposure (eq. (7)) are given. Short-time and long-time results are shown in figures 1 to 5 by dashed and solid lines, respectively. Three values for the solar radiation, 314, 628, and 942 W/m^2, were used. These values are typical of the range of solar radiation determined from National Weather Bureau data tapes for Langley Air Force Base, Hampton, Virginia, during 1962 and from relationships found in reference 11.

Figure 1 shows the effects of absorptance α on M/M_a. High values of α result in more heat absorbed, high temperature, and low relative humidity.

Thus, temperature T and humidity ϕ of the air next to the panel diverge from the ambient condition at high values of α. The moisture ratio exceeds a value of one for small values of α at low values of q because the panel is cooled below ambient temperature. Values of α typical of flat-black silicone paint, grey silicone paint, gloss-white silicone paint, and polished aluminum are 0.89, 0.53, 0.26, and 0.1, respectively. (See ref. 12.)

Figure 2 shows the effects of emittance ε on M/M_a. High values of ε result in more heat reradiated from the panel, low temperature, and high relative humidity. Thus, temperature T and humidity ϕ of the air next to the panel approach the ambient condition at high values of ε. Values of ε typical of flat-black silicone paint, grey silicone paint, gloss-white silicone paint, and polished aluminum are 0.81, 0.96, 0.75, and 0.05, respectively. (See ref. 12.)

Figure 3 shows the effects of the convective heat-transfer coefficient h on M/M_a. High values of h result in cooling the panel, low temperature, and high relative humidity. Thus, temperature T and humidity ϕ approach the ambient conditions at high values of h. Heat-transfer coefficients of 11.4 and 34 W/m^2-K correspond to low-speed laminar flow over a flat plate at velocities of about 3 and 26 m/sec, respectively.

Figure 4 shows the effects of ambient temperature T_a on M/M_a. At high values of T_a, the temperature difference between the ambient air and the air at the surface is small, ϕ approaches ϕ_a, and M/M_a approaches a value of one.

Figure 5 shows the effects of the orientation of the panel on M/M_a. At high values of the angle ψ between the normal to the panel and the Sun, the amount of radiation incident on the panel is small. Thus, the value of T is low, the value of ϕ is high, and the values of both T and ϕ are close to the ambient values. For $\psi \approx \pi/2$ rad, solar radiation incident on the panel is close to zero, reradiation cools the panel below the ambient temperature, and M/M_a has values greater than one.

In all cases, the moisture ratio varies significantly over the range of values used for the parameters. The value of moisture ratio can be greatly different from one. The deviations from a value of one are less for short-time exposure than for steady-state exposure because, for short-time exposure, the temperature-dependent diffusion coefficient appears explicitly in the expression for M/M_a and a high surface temperature results in a large diffusion coefficient which compensates for a low value of ϕ at the surface.

Collectively, the results show that moisture content based on ambient conditions can significantly overestimate or underestimate the moisture in an exposed panel. The moisture ratio has the same trends with respect to each parameter for both short-time exposure and steady-state exposure, but the moisture ratio was more sensitive to all parameters considered for the steady-state condition.

Moisture-Ratio Sensitivity to Energy-Balance Parameters

Fabrication processes and exposure to service environments may result in values for parameters in the energy-balance equation (1) that are different from the expected values. The sensitivity of M/M_a to the values of these parameters is shown in table I; the sensitivity of M/M_a to the parameters depends on the exposure time and the magnitude of the solar radiation. The moisture ratio is more sensitive to the parameters for long-time exposure than for short-time exposure. For both exposures, M/M_a is more sensitive to a practical range of values for α and h than to a practical range of values for the other parameters. At steady state, the moisture-content ratio M/M_a can be as much as 24 percent less for $\alpha = 0.8$ than for $\alpha = 0.7$ and 25 percent more for $\alpha = 0.8$ than for $\alpha = 0.9$. At steady state, M/M_a can be as much as 44 percent less for $\alpha = 0.26$ than for $\alpha = 0.16$ and 28 percent larger for $\alpha = 0.26$ than for $\alpha = 0.36$. Therefore, a high value of α would result in low moisture content, and the sensitivity of M/M_a to values of α would be less.

Of all the parameters considered, the heat-transfer coefficient h had the largest effect on M/M_a. At steady state, M/M_a could be as much as 64 percent less for $h = 11.4\ \mathrm{W/m^2\text{-}K}$ than for $h = 17.1\ \mathrm{W/m^2\text{-}K}$ and 53 percent greater for $h = 11.4\ \mathrm{W/m^2\text{-}K}$ than for $h = 5.7\ \mathrm{W/m^2\text{-}K}$.

CONCLUSIONS

The influence of surface and environmental thermal properties on the moisture absorption in fiber-reinforced polymeric-resin-matrix composites subjected to convection and solar radiation has been studied analytically. The properties considered were solar absorptance, emittance, convective heat-transfer coefficient, ambient temperature, solar radiation, and panel orientation with respect to the Sun. Predicted moisture content based on conditions at the heated surface and in ambient air was compared for both short-time and long-time (steady-state) exposures. (Short-time exposure corresponds to about 5 days or less for the T300/5208 graphite epoxy composite at 300 K.)

The results of the study lead to the following conclusions:

1. Generally, when radiation and convection effects are included, moisture content is less than that of a shielded panel. However, if the panel is cooled, the moisture content could be greater than that of a shielded panel.

2. Moisture content varies significantly with variations in each of the parameters.

3. The sensitivity of the moisture content to the value of the parameters is less for short-time exposure than for long-time exposure because moisture content for the short-time exposure is a function of the temperature-dependent diffusivity.

4. High values of solar absorptance and low values of surface emittance result in low moisture content.

5. Moisture content is more sensitive to realistic variations in the heat-transfer coefficient than in the other parameters considered. The steady-state moisture content for a heat-transfer coefficient of 11.4 W/m^2-K can be as much as 53 percent greater than the moisture content for a heat-transfer coefficient of 5.7 W/m^2-K.

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August 8, 1977

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TABLE I.- SENSITIVITY OF MOISTURE-CONTENT RATIO TO ENERGY-BALANCE PARAMETERS

Energy-balance parameter	Range of values	Change in M/M_a, percent					
		Short-time exposure at q, W/m^2, of -			Long-time (steady-state) exposure at q, W/m^2, of -		
		314	628	942	314	628	942
α	0.8 ± 0.1	±5	-9 to 10	-10 to 13	-12 to 10	-18 to 21	-24 to 25
α	0.26 ± 0.1	-6 to 10	-11 to 13	-14 to 18	-12 to 14	-21 to 29	-28 to 44
ϵ	0.8 ± 0.1	±3	4 to -5	±6	6 to -7	10 to -7	12 to -10
h	11.4 W/m^2-K ± 50%	9 to -15	19 to -25	24 to -29	21 to -30	±47	64 to -53
T_a	294 K ± 2%	1 to -2	3 to -4	6 to -7	2 to -3	7 to -8	13 to -10
ψ	$\pi/4 \pm \pi/8$	7 to -6	11 to -9	16 to -12	15 to -12	28 to -19	38 to -22

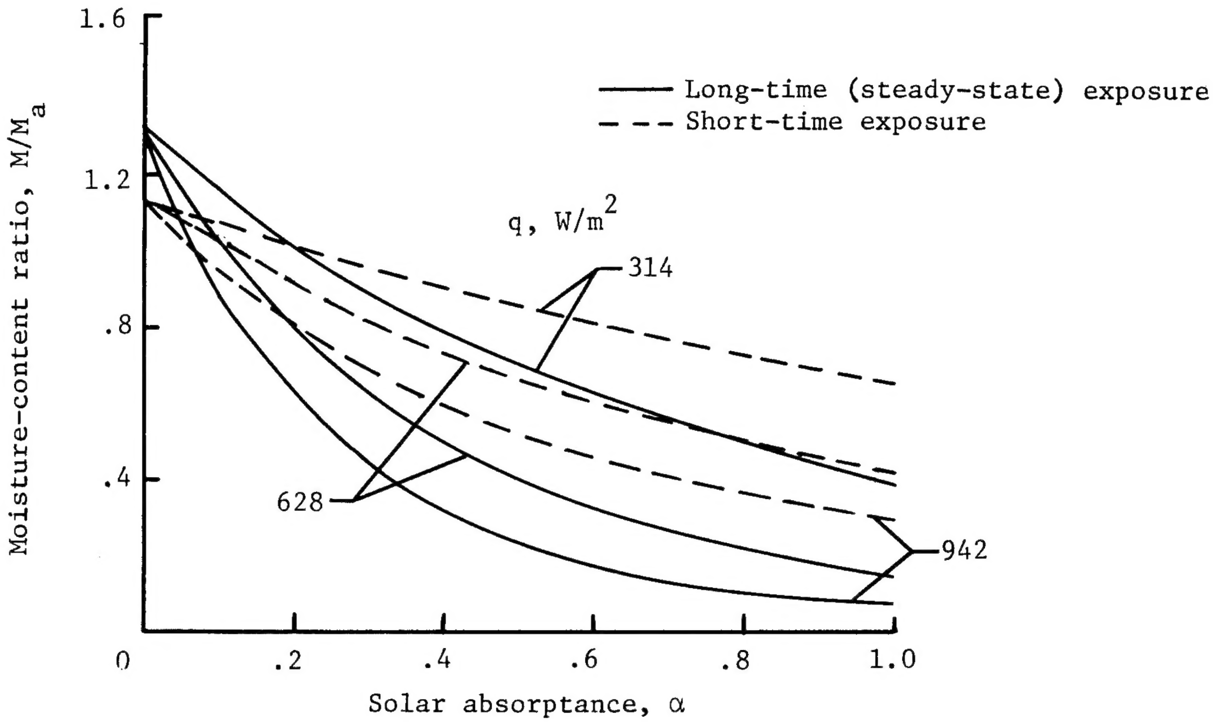

Figure 1.- Effect of solar absorptance on moisture-content ratio. $\varepsilon = 0.9$, $h = 11.4\ W/m^2\text{-}K$, $\psi = 0$, and $T_a = 294$ K.

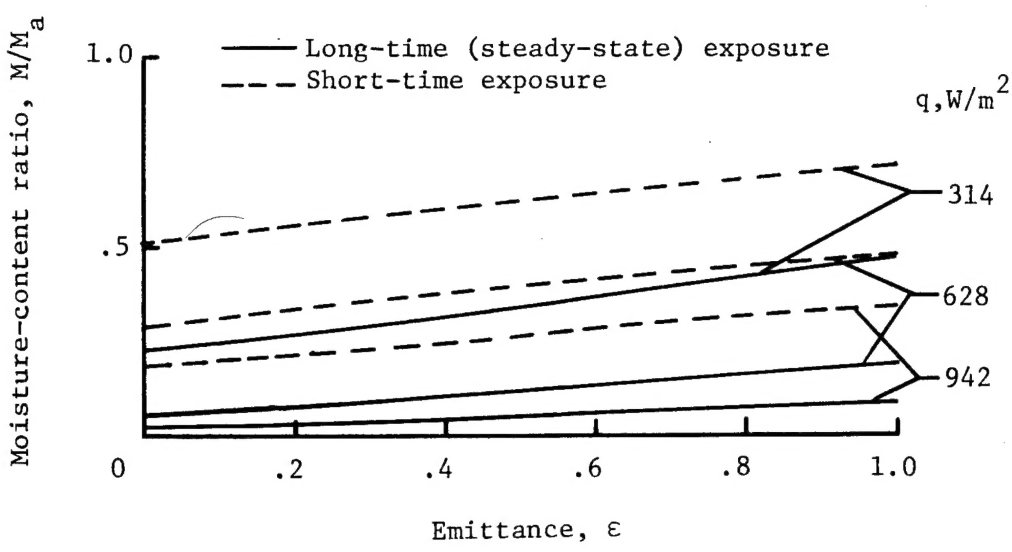

Figure 2.- Effect of surface emittance on moisture-content ratio. $\alpha = 0.9$, $h = 11.4\ W/m^2\text{-}K$, $\psi = 0$, and $T_a = 294$ K.

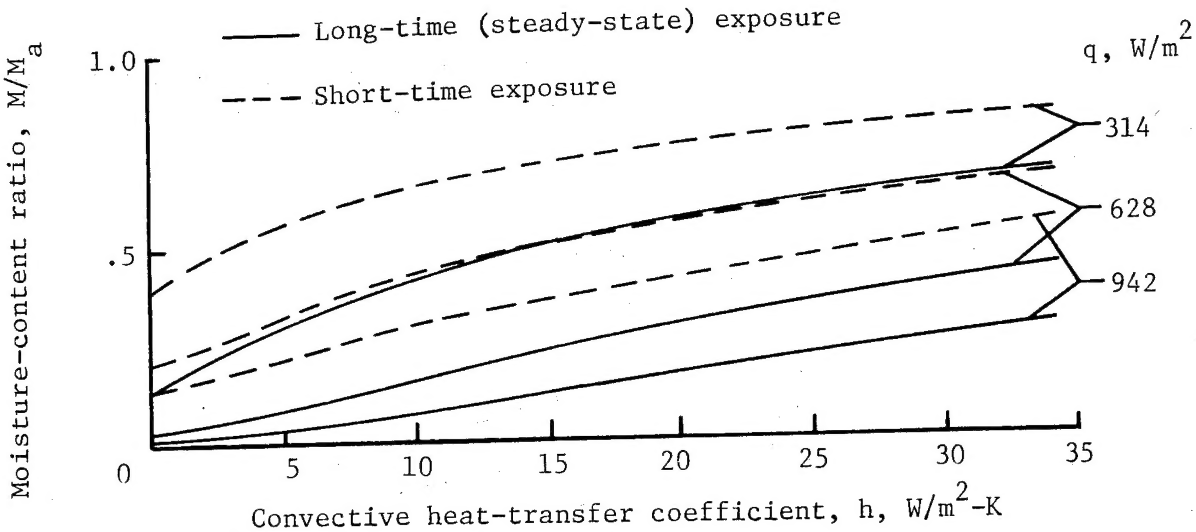

Figure 3.- Effect of convective heat-transfer coefficient on moisture-content ratio. $\alpha = 0.9$, $\varepsilon = 0.9$, $\psi = 0$, and $T_a = 294$ K.

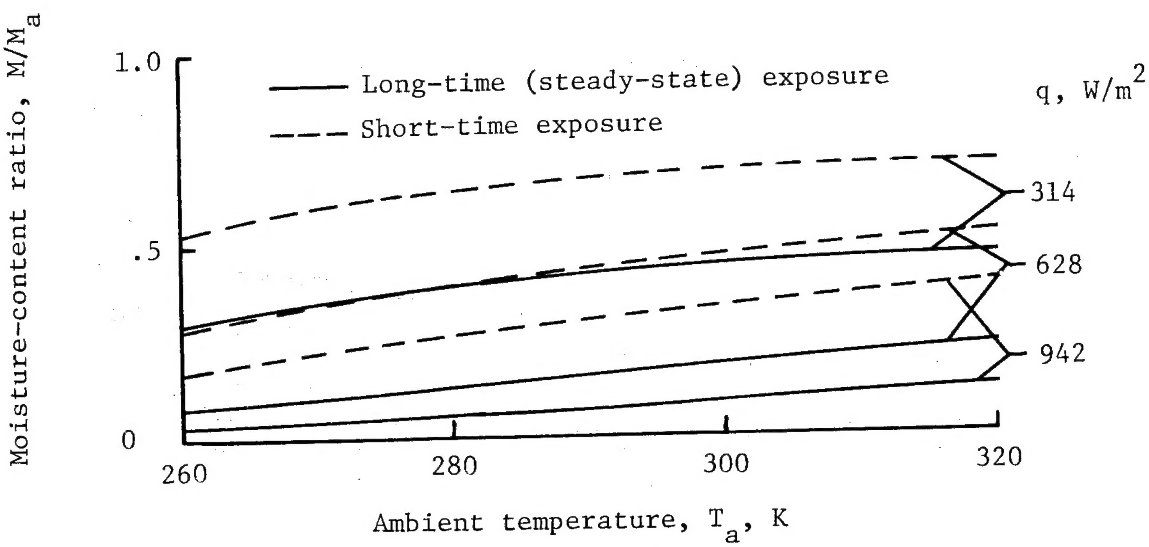

Figure 4.- Effect of ambient temperature on moisture-content ratio. $\alpha = 0.9$, $\varepsilon = 0.9$, $h = 11.4$ W/m^2-K, and $\psi = 0$.

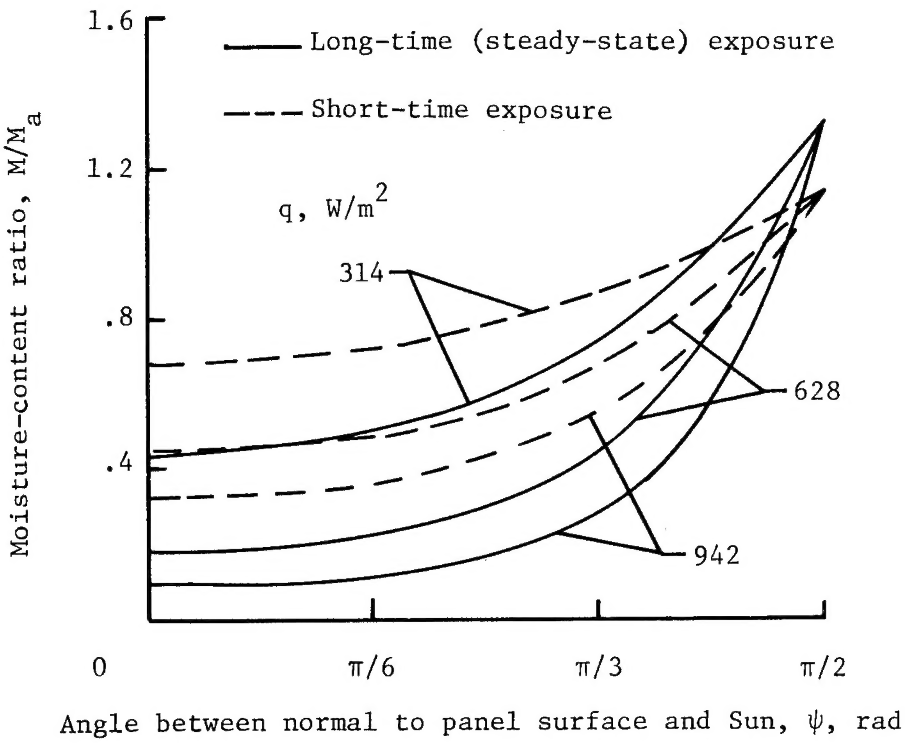

Figure 5.- Effect of surface orientation on moisture-content ratio. $\alpha = 0.9$, $\epsilon = 0.9$, $h = 11.4$ W/m^2-K, and $T_a = 294$ K.

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